IMAGING SCIENCE TECHNOLOGIES

F&M BANK BUILDING • PO 8175 • CHARLOTTESVILLE, VA 22906 • 804/978-7000

FINAL REPORT SDIO PHASE I

INFRARED SENSOR AND IMAGING SYSTEM

CONTRACT DASG60-88-C-0123

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ADVANCED IMAGING SYSTEMS

1. EXECUTIVE SUMMARY

The technical objective of Phase I was to investigate the feasibility that thin film compounds shown in the contractor's patent were feasible for use as an un-cooled infrared (IR) sensor and imaging system. Research included formulating and optically testing thin films to demonstrate a photonic IR process operable near 10 microns with a minimum resolvable temperature of 0.1°C. Also, a theoretical study of an IR camera was to be conducted.

The technology is based on quadratic non linear processes for use in a device for un-cooled thermal imaging and the contractor believes this may be the only photonic IR process which affords the direct conversion of an IR signal into a visible one in real-time with no electronic circuitry or cooling being required for this.

Since the contract was awarded, the patent has now been issued as U.S. Patent 4,751,387 and assigned to the contractor's President. This patent is included at the end of this final report to SDIO.

The contractor believes that the results obtained in Phase I are remarkable and exceed the technical objectives of Phase I. Not only was the feasibility proven, but the patent was reduced to practice with IR images recorded over a 19°C temperature range with a minimum resolvable temperature of 0.1°C. A photograph of an actual recorded image (hand) is shown with the issued patent.

The test system was comprised of a synthesized photodichroic thin film coated onto a nitrocellulose pellicle in a feasibilty IR camera that produced images (hand) over a wide temperature range (19°C) with an accuracy of 0.1°C. Response time is believed to be in the submicrosecond range and possibly in the nanosecond range.

The response time was not measured exactly, but this will be part of the contractor's Phase II submission to confirm that this is a purely photonic mechanism along with optimization of the photodichroic film to attain a 0.01°C minimum resolvable temperature. The optical arrangement of the test system is shown in Figure A.

The contractor believes that this IR sensor & imaging technology has direct application for SDIO missions in surveillance, target acquisition and discrimination. The contractor's Phase II Proposal will address proposed applications such as: HEDI, Brilliant Pebbles and a Synthetic Aperture Fly's Eye Staring Telescope (SAFEST) networking 19 IR cameras for space-based surveillance.

This un-cooled, photonic process may present a breakthrough in the field of IR thermal imaging. It relates to resonant molecular optics which describes an enormous enhancement of non-linear signals where the incident electromagnetic field frequencies match those of the optical transitions which are peculiar to the molecular species present. Another description of the same effect is termed parametric amplification due to quadratic polarization.

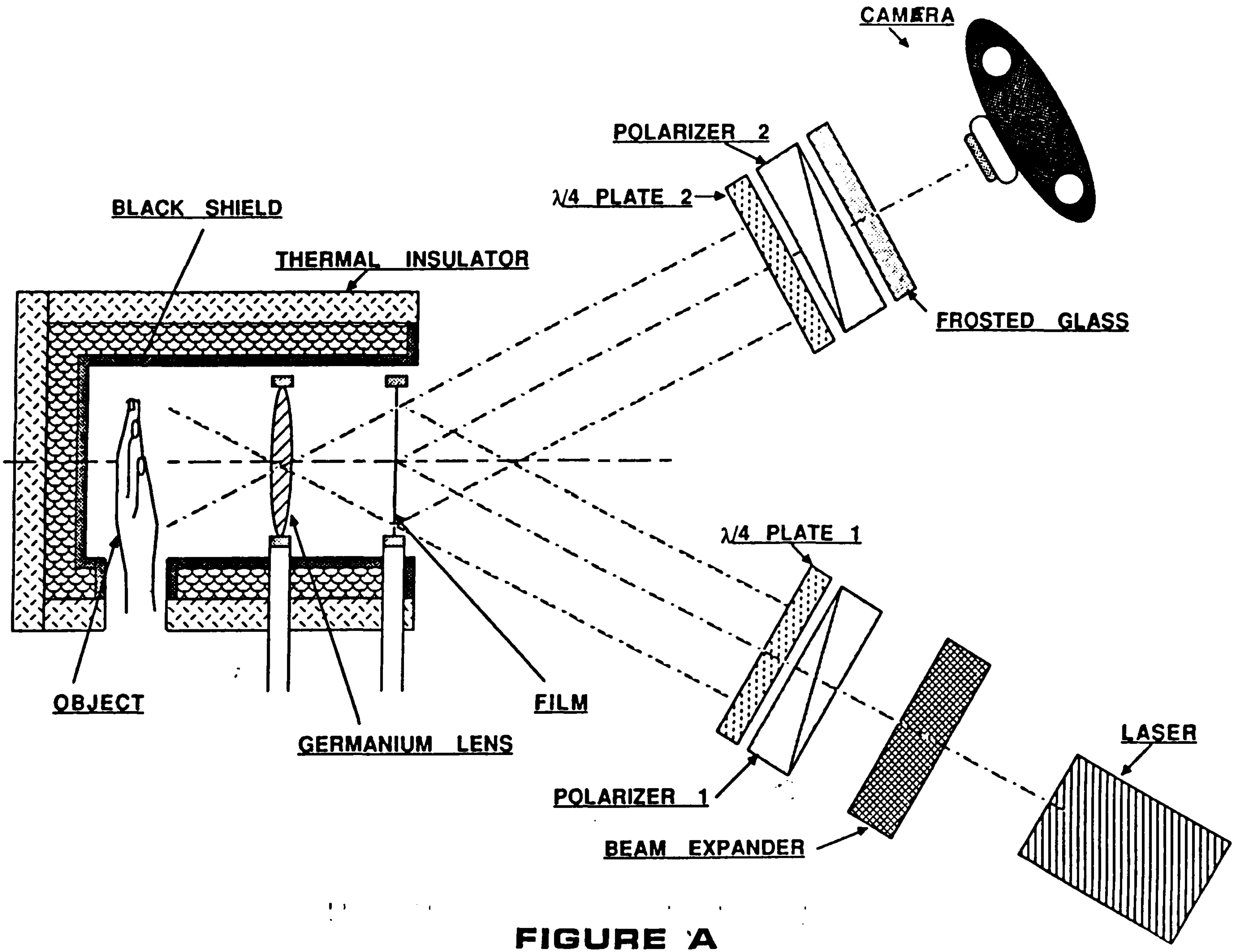
CAMERA
POLARIZER 2
λ/4 PLATE 2
BLACK SHIELD
THERMAL INSULATOR
FROSTED GLASS
λ/4 PLATE 1
OBJECT
FILM
GERMANIUM LENS
LASER
POLARIZER 1
BEAM EXPANDER

FIGURE A

2. PRINCIPLE OF UN-COOLED REAL-TIME PHOTONIC IR IMAGING

This Un-cooled Sensor & Imaging System (US Patent 4,751,387) has applications both as a far infrared camera and a night vision system with high sensitivity/resolution, sub-microsecond response time and low cost. It is based on the change in dichroism induced in certain Photodichroic (PD) polymers; e.g., Polyacetylenes, Liquid Crystals (LC), et al, as a result of IR photon absorption, and provides for the direct conversion of an IR signal into a visible one without requiring electronic circuitry.

This is a Photonic, not Thermal, process; i.e., the term Photonic is generally used in IR to characterize detection systems based primarily on electronic transition produced by an absorption of IR photons affording microsecond response time. The term Thermal relates to detectors which involve a temperature sensitive phenomenon such as conductivity (bolometers) or dielectric constant. These involve mostly increases in temperature proportional to the specific heat of the material with millisecond response times.

Thermal imaging is costly as the detectors, scanners, cryogenics, maintenance and lenses are expensive. The PD method uses only a standard IR lens and thus solves most cost problems immediately.

A lens, e.g., germanium, is used to form an IR image on a membrane and a circularly polarized light provides illumination of the membrane at non-normal incidence. Analyzing the polarization of that light after reflection from the membrane provides a visible image by means of ellipsometry. The contrast mechanism is a result of changes in the optical properties of the PD film due to local variations in the index of refraction.

We propose to image a thermal scene onto a very thin film which holds a PD film optimized for an electronic transition occuring near 10 microns. By viewing this film through visible ellipsometry, minute changes in optical properties can be observed either directly or by CCD camera. This thermal to visual image converter can replace near IR tubes now used for NV and FLIR and serve as an IR tracker/imager for next-generation smart weapons.

Although we have identified PD materials superior in performance to LCs a review of general characteristics of LCs is instructive. LCs are well known as temperature sensors used as human thermometers, circuit component temperature indicators and radar field pattern transducers. The extremely low power required to visually change numeric patterns on LC wrist watches (5 year battery) is well known. In this system, viewing the display through a type of polarimetry generates numerals with a high visual contrast.

The optical properties of LCs then, are affected by very small amounts of energy, not only thermal, but also by photodichroism.

Both nematic and cholesteric LCs undergo changes in refractive index with input energy of 10-(-14W)sec/cm-2. Efforts in LCs have been directed toward the use of electrical energy in optical displays (1), thermal energy in temperature sensors/thermal mapping (2), and other types of energy are also being considered (3). The extreme sensitivity of LCs warrants their use for the detection and measurement of radiant energies, particularly IR energy where they can be used in a thin film form for an imaging device.

The sensitivity already achieved for thermal measurement suggests a detectivity approaching or equal to existing IR detection and imaging systems. The best way to benefit from the remarkable sensitivity of PDs for IR imaging is to convert directly the absorption of IR energy by the material into a change of refractive index that will directly modulate the transmission or reflection of light in a display configuration; i.e., a thin film PD plays the dual role of IR detection target and display screen.

This technology makes use of the dichroism of certain PDs coated onto a thin membrane using the Langmuir-Blodgett method. When a thermal scene is imaged upon the membrane, local variations of index of refraction in the PD layer are induced according to the illumination level. Note that this approach uses a very thin film (20 millimicrons thk) and is not related to the work done with LCs by the US Army NV Labs or companies in the 1960s & 70s.

This IR sensor/imaging technology is a photonic system that relies on the optical properties of the material rather than its thermal properties; and where the mechanism of energy transfer in the photodichroism is purely electronic affording sub-microsecond range response times. The photodichroism is caused by a direct transfer of energy from IR photons absorbed by the electrons in the PD structure, not a temperature increase. Most importantly, this affords a device operating at room temperature not requiring any expensive cryogenic cooling and maintenance.

Depending on how the sensor is engineered, excess energy is eventually dissipated within a certain time in the form of heat. However, the electronic interaction responsible for the change in index of refraction has already occurred which is very important from the point of view of speed and sensitivity. Since it is not possible to completely neglect this aspect, this thermal energy can be cancelled out as it is a constant or completely blocked by methods now under consideration to be employed in a final design.

The mechanism of IR imaging using photodichroic materials relate to the electronic theory of dichroism (7) (8)) that is based on a coupling interaction between different atomic groups of the molecules. The IR absorption is generally localized on specific groups which upon absorption of IR energy modify their couplings with other groups of the same molecule and thereby the dichroism of the material. As dichroism is characterized by two components of the polarized wave corresponding to two indices of refraction, a variation in dichroism is related to the change in the indices.

The key to the superiority of this new technology is the combination of ellipsometry, a very sensitive method used to measure dichroism, with the variation of dichroism (ellipticity) caused by the absorption of infrared energy. The prospect for a successful product is high based on two simple considerations:

1) Ellipsometry is one of the most sensitive methods to detect very small changes in optical properties. Optical layers of less than one Angstrom and very small changes in index of refraction are currently measured. 2) Dichroic materials with an absorption band in the 10 micron range show a drastic modification in their optical properties (ellipticity of transmitted or reflected light in the visible) when they are exposed to IR photons.

The second item is mainly due to the coupling of single electrons responsible for variations in the index of refraction (coupled oscillator theory)(1) to larger functional groups involved in the absorption of IR photons. Ramachandran (6) has calculated the dichroism of materials with spiral structures similar to cholesterics LCs according to a classic 1st order polarizability theory obtaining reasonably good agreement with measured values.

The phenomenon of resonant molecular absorption, sometimes called 2nd order hyper polarizability in nonlinear optic terms, has been observed (17).

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3. RESEARCH CONDUCTED IN PHASE I

3.1 SIGNIFICANCE OF RESULTS

The successful results of Phase I will enable the contractor to submit a Phase II Proposal for optimizing the film to a minimum resolvable temperature (MRT) of 0.01°C and building one or more prototype IR cameras for testing to show the appropriateness of this process for use in remote thermal imagery for SDIO missions.

Attainment of Phase II goals will result in the design for an un-cooled IR system with a minimum accuracy of 0.01°C covering a temperature range over 50°C. A 19°C temperature range has already been achieved in Phase I (see section 1) and this needs only to be extended in Phase II.

This device will cost only a fraction of that of existing IR systems which cost about $100,000. This cost is now a signficant part of a typical complete thermal imaging system.

3.2 RESEARCH CONDUCTED

The following is an overview of the Phase I research conducted:

a) Selection and formulation of the dichroic compounds

b) Establish procedure for coating thin film compounds

c) Selection of pellicles to be used as film substrate

d) Selection of alternate film substrate methodologies

e) Selecting method of a camera design from the patent

f) Investigation of another alternative camera design

e) Measurment of minimum temperature change sensitivity

f) Establish optical conditions to view a thermal image

g) Successful demonstration of un-cooled thermal imager

The following pages describe in detail the research conducted during Phase I with appropriate drawings, diagrams and tables. The reviewer is referred to the Appendix to view the photograph of an actual IR image (taped to the front of US patent) made in Phase I which evidences the reduction to practice of the patent.

3.3 SELECTION AND FORMULATION OF THE DICHROIC COMPOUNDS

Several cholesteric liquid crystal compounds were prepared for coating onto pellicles and testing. These compounds were analogs of cholesterol possessing large alkyl groups in the 3 Beta position increasing the hydrophobicity. Several analogs were coated onto nitrocellulose pellicles. Once coated onto the membrane, they were placed in an electric field to align the liquid crystals.

Between various camera designs and membrane inconsistencies, we were unable to obtain any recordable results with the cholesteric liquid crystals. This does not mean liquid crystals are not a viable dichroic compound as we believe the lack of results may have been more of a problem with the camera/optics. Further work will be done in Phase II for optimizing a liquid crystal film.

Various photodichroic compounds were recommended by Dr. J. J. Robillard who is now a consultant to the applicant. He is the inventor of US Patent 4,751,387 which is the basis of our proposal. These were chosen based upon their non-linear optics properties and availability. One of these was used for the successful test.

The successful results of Phase I shown in this Final Report in demonstrating feasibiltiy were based on using this compound. All test results and the photo in the appendix are based on this compound. SBIR instructions specifically state not to include any Proprietary information in proposals and as we consider this information to be proprietary, only a diagram of the basic molecule is shown below in Figure B without the exact chemistry.

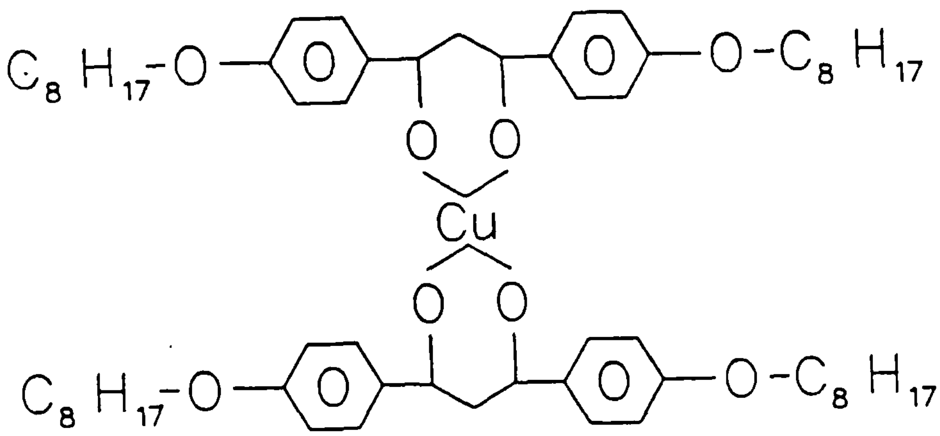

FIGURE B

3.4 ESTABLISH PROCEDURE FOR COATING THIN FILM COMPOUNDS

Because the optimized thin film layer is very thin (20 milli-microns), the Langmuir-Blodgett monolayer film coating technique was determined to be the optimum means of coating the film. This grant did not include enough funding to buy a system ($42,000+), so an apparatus was designed to mimic the Langmuir-Blodgett (L-B) film coating machine to prove feasibility.

The procedure is to start with a solution of the desired compound to be coated in a solvent (acetone/chloroform). The concentration of this will be determined by the size of the film and thickness.

Figure C depicts the Thin Film Coating Machine used to mimic the L-B process. A nitrocellulose pellicle with its flat edge down is placed at the bottom of of the unit. The container is filled with liquid until the level is 1 cm above the top of the ring. A few drops (amount is calculated according to the concentration of the solution, the diameter of the vessel and the desire thickness of the membrane) are spread over the surface of the liquid.

After evaporation of the solvent, the liquid is slowly evacuated through the bottom and the membrane stretches itself over the edge of the top of the ring. Carefully, the pellicle is then moved to a dessicator and allowed to stand over night at 60°C. Once dried, the pellicle is then reading for testing.

3.5 SELECTION OF PELLICLES TO BE USED AS FILM SUBSTRATE

In addition to being coated onto pellicles, the dichroic film could be self-supporting polymerized films. This could increase sensitivity, but the scope of Phase I did not include this. As it is an alternative, it is discussed briefly here. the film would be formed on a metal ring and held by its own surface tension (like a soap bubble) while an ultraviolet light polymerized in situ. The L-B process and others are particularly suitable for production quantities of very uniform films. As these processes were unavailable for reasons described in 3.4, an alternative was sought to demonstrate feasibility.

Any substrate film must possess a number of physical properties so that the photodichroism process has a good chance of working. Pellicles were chosen for reasons to be discussed here. Pellicles are normally used as near-zero path length beam-splitters and as optical combiners.

They are made of tightly stretched nitrocellulose films supported by metal rings. Because pellicles are used as beam-splitters, they must be non-birefringent and optically flat. These qualities ensure that it is the coated photodichroic film which causes bi-refringence and not the substrate. Related to these properties is the near-zero internal stress condition exhibited by pellicles where this internal stress would act to create birefringence.

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THIN FILM COATING MACHINE

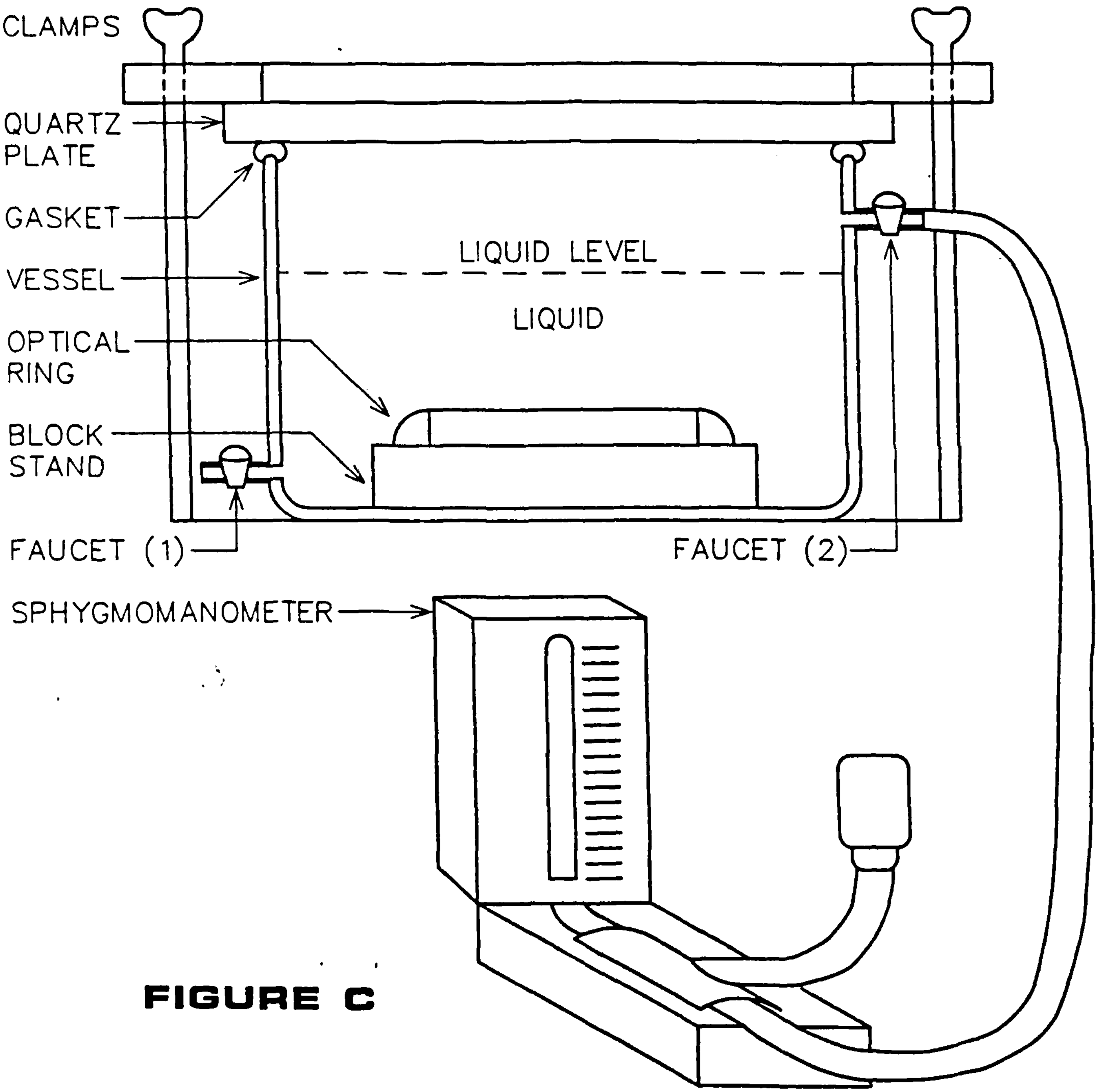


FIGURE C

3.5 CONTINUED

Two different thicknesses of pellicles were used, 2.0 microns and 5.0 microns, as coating substrates. Because the nitrocellulose is so thin, any local heating due to varying regions of incoming thermal flux (as would be expected at the image plane of a thermal imaging lens) will be dissipated rapidly enough to observe real-time imagery.

Also, the thin nitrocellulose substrate has a limited effect on localized heating of photodichroic film. A thick substrate would store relatively large amounts of heat due to its volume, absorb proportionately more heat due to its increased path length, and slow down the thermalization process for changing scenes.

Pellicles made of nitrocellulose are remarkably strong for their thin dimensions. Since the coating method is at a somewhat crude state of development, the strength is necessary to withstand the manual coating operation. Another most important quality of pellicles is their size and availability.

A one inch diameter central uniform coating was desired in order to provide a one inch image plane. Since the wetting angle of the photodichroic materials makes the coatings thick at the edges, two inch diameter pellicles were selected. This insured that the central portion would be very thin and uniform.

3.6 SELECTING METHOD OF A CAMERA DESIGN FROM THE PATENT

From the patent, several methods of obtaining the thermal image of a scene are shown on Figure D. A design similar to inset #4 was considered. The design was modified slightly and is shown in Figure E.

At the entrance to the camera is a Zinc Selenide (ZnSe) window which is very transparent to thermal radiation around and beyond 10 micron wavelength. ZnSe is also transparent to Helium-Neon (HeNe) laser light at 633 nm. The thermal imaging lens was located outside the camera cell in order to allow focusing without breaking the vacuum of the cell (to be discussed later).

The thermal target was located beyond the imaging lens which was an f/2, focal length at 100 mm, plano-convex germanium lens. The imaging lens then projected an image of the target onto the coated pellicle through the ZnSe window.

In between the imaging lens and the ZnSe window was placed a flat disc of germanium at 90° to the optical axis. This fold mirror was transparent to the thermal radiation, but allowed the HeNe light to be folded in. The HeNe light was beam expanded to a one inch diameter before being folded onto the thermal imaging path. As such, the light existed in collimated form and thus uniformly illuminated the central one inch dia. portion of the pellicle.

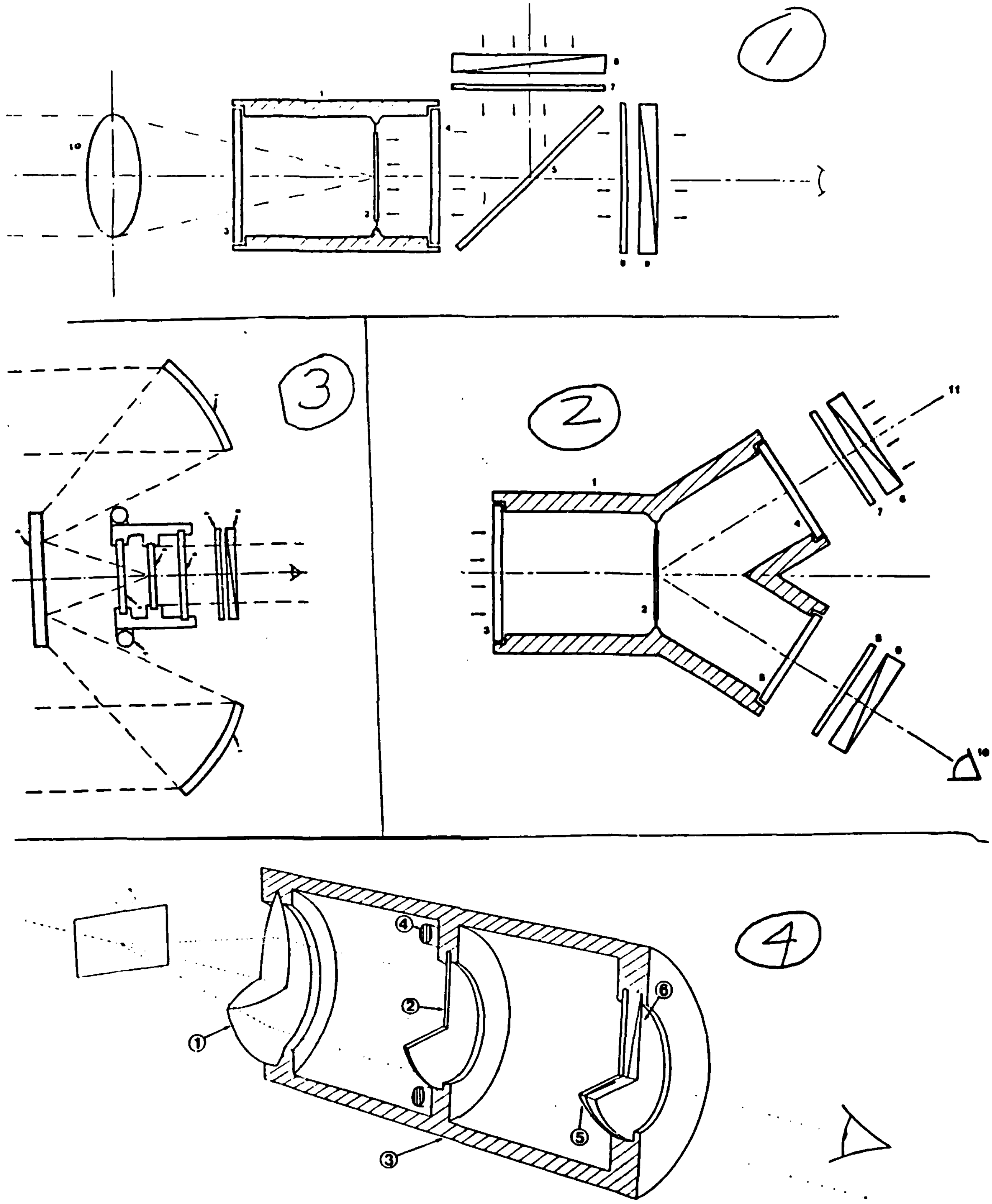
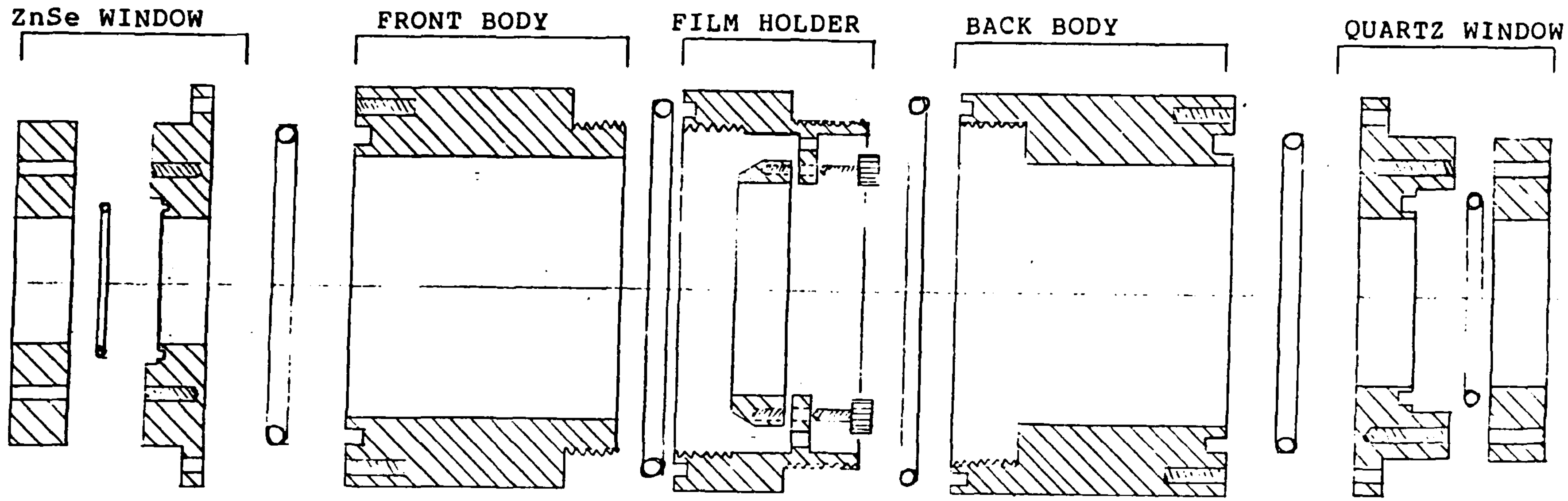


FIGURE D



CAMERA BODY

APPROXIMATELY 3" DIAMETER X 12" LONG

FIGURE E

3.6 CONTINUED

Thus, the thermal image and the collimated laser beam together illuminated the pellicle. The laser light was circularly polarized and was intensity controlled before being folded into the optical path. From the opposite side of the cell, the laser light passed through a quartz window where there was another quarter wave plate and analyzer.

All thermal windows and lenses were anti-reflection coated at 10.6 microns since they are commercially available because of commercially available carbon dioxide laser products. The coating was therefore not optimized at 10 microns, but very nearly so.

Custom coating services were prohibitively expensive and involved long lead times. The focal length of the germanium plano-convex lens was chosen to eliminate any indirect radiation effects which might occur for very short focal length lenses. It would have been a "faster" lens at f/1, but there was concern about the adverse effect of spherical aberration which is a problem in fast single element lenses. In terms of feasibility, the spherical aberration wouldn't have mattered. The successful tests were done using an f/1, focal length 50 mm germanium lens.

The cell itself is made of thick aluminum and is incapable of supporting a heat gradient. This is important in an un-cooled camera such as this as otherwise, hot spots in the camera radiate the pellicle non-uniformly creating unwanted image patterns.

The cell is at some very uniform temperature depending on the environment. The insides of the cell are painted with high emissivity black paint. In such a condition, the film will see a highly uniform isotropic flux of infrared light except for the direction where the target source is located. Then, any observed changes in uniform background polarization will be changes due to a thermal image projected onto the pellicle by the imaging lens.

The cell is designed to facilitate a quick and easy method of changing pellicles. A vacuum pump is used to evacuate the interior of the cell so that convection currents are eliminated.

The cell as designed and fabricated from inset #4 on Figure D, was not successful in obtaining images and will be redesigned, contingent upon a Phase II award, in accordance with the configuration shown in inset #2 on Figure D. The succcessful feasibility tests were accomplished using this #2 configuration. No vaccuum was used, however, a uniform background was present.

3.7 MEASUREMENT OF THE MINIMUM TEMPERATURE CHANGE SENSITIVITY

For these measurements, the coated pellicles were arranged as shown in Figure A. Three (3) tantalum metal foil strips were suspended between two (2) quartz rods as shown in Figure F. A controlled and requlated current was passed through each strip.

Because tantalum is a rather poor conductor of electricity, the current in the strips generates Joule heat and the temperature of the foil strips is consequently raised. By passing more or less current through the strips, a higher or lower temperature may be arranged.

Each step had a thermocouple attached to its back-side. Thus, it was possible to manually adjust a current through each strip so that a desired temperature could be stabilized and monitored.

The mounted tantalum strips were placed at the image plane shown in Figure A (Optical Arrangement). Various temperatures ranging from 18°C to 37°C were produced in various currents through the strips.

For each set of temperatures, the exact temperature was recorded while the laser beam intensity was measured and adjusted for maximum image contrast. The resulting image was then photographed. Next, a new set of temperatures was arranged and the preceding process repeated. After all temperature ranges were completed, the film was developed. (see Appendix for image photo)

The temperature ranges used were selected to span the ordinary skin surface temperatures occurring under a variety of biological conditions. A series of three strips of varying optical density appeared on the developed film corresponding to the thermal image of the tantalum strips.

It was then possible to measure the optical density of each strip relative to a part of the image which did not contain the strip. In this way, an optical density was quantitatively associated with each temperature. Alternatively, the negatives could have been printed as in the ordinary photographic process.

Then the optical densities would have been converted into image contrast in the form of various shades of grey. As the latter process leads to a subjective evaluation, the former method was chosen as being more objective.

The raw data is shown in Table I. The three strips showed slightly differing temperatures for each range. Corresponding changes occurred for the optical densities. For illustration, an average of each group of the three similar temperatures is plotted against the corresponding average of the three respective optical densities in Figure G.

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TEMPERATURE TARGET STRIPS MOUNTED ON QUARTZ RODS

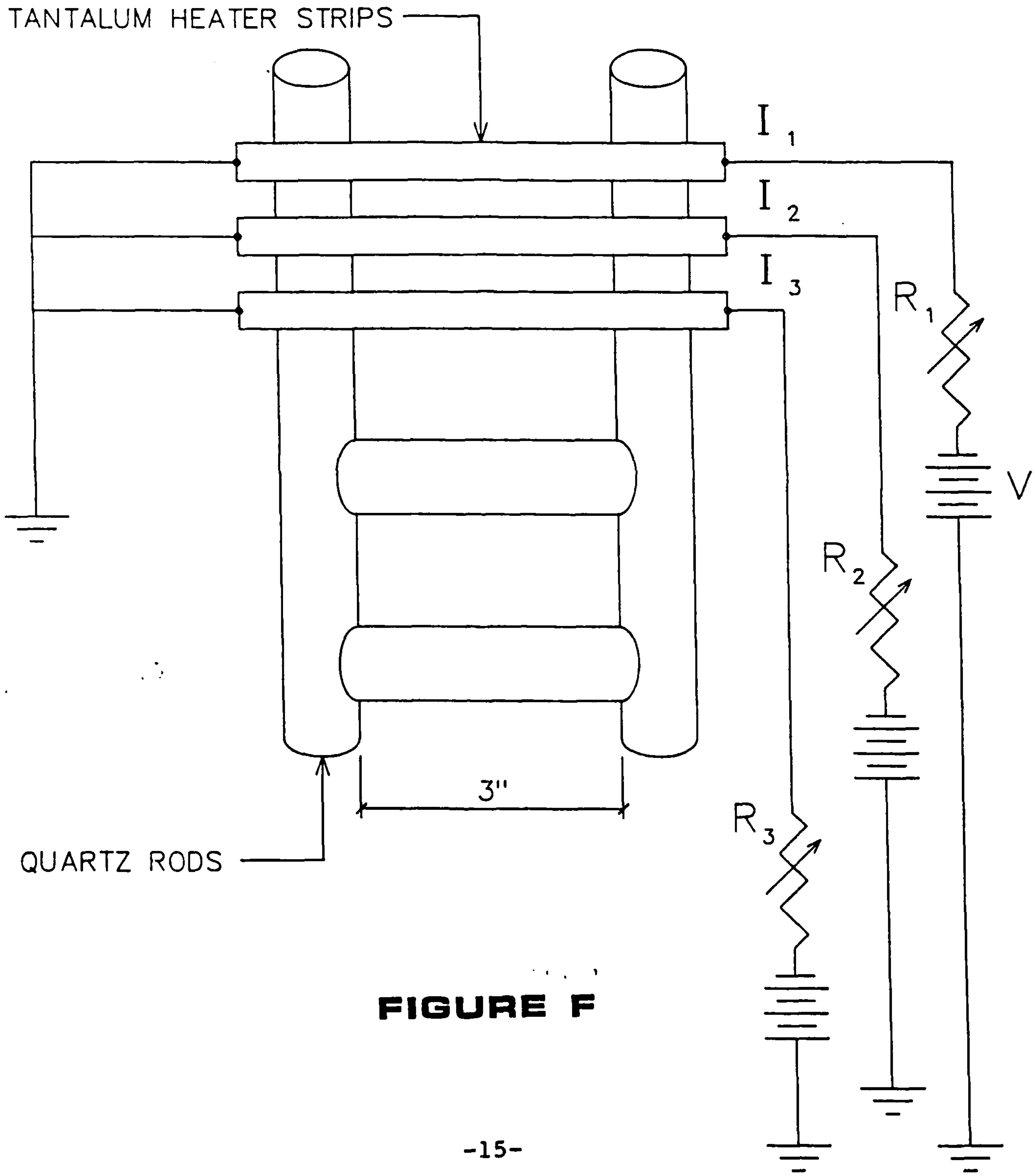
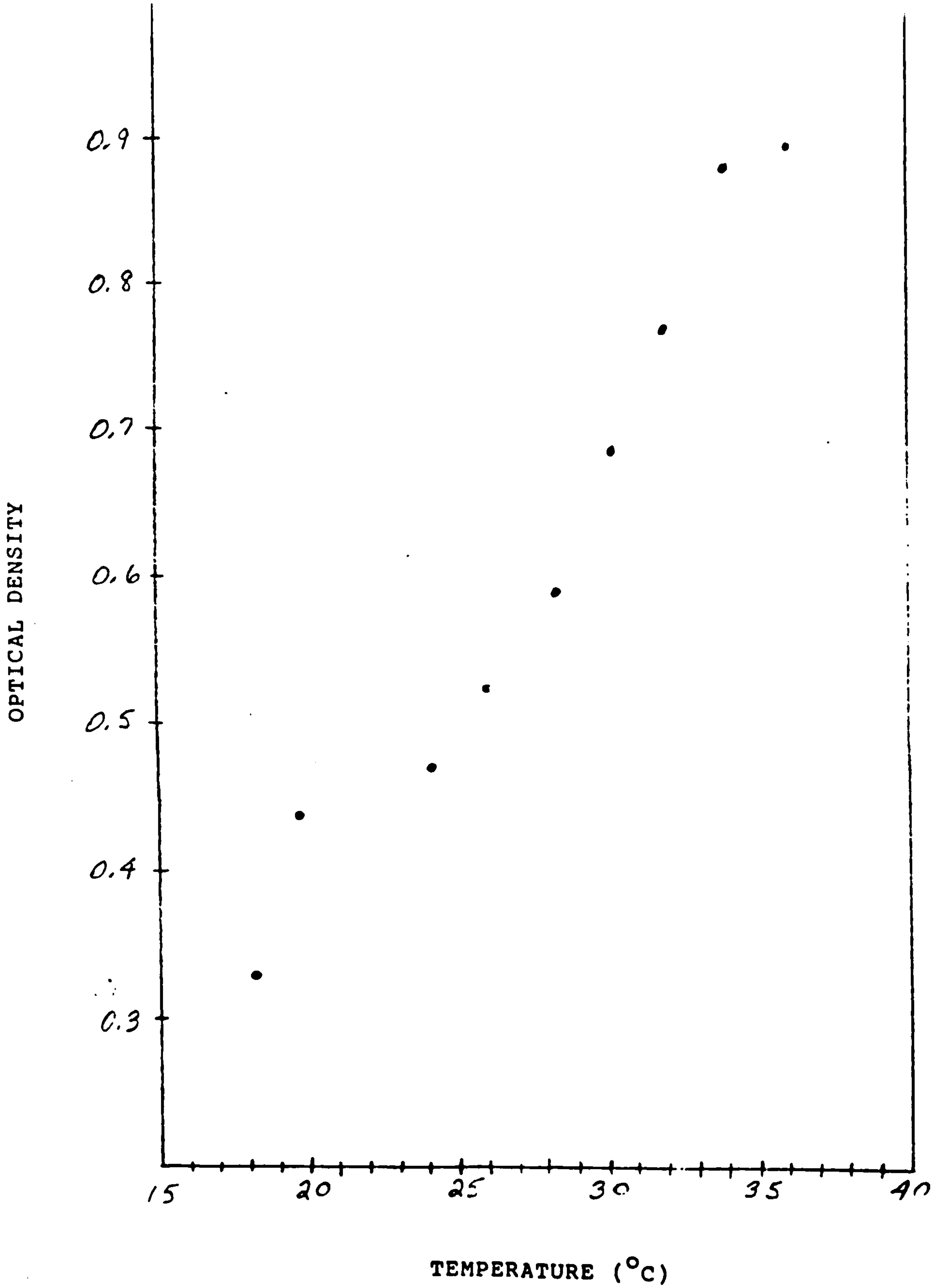


FIGURE F

AVERAGE TEMPERATURE °C	STRIP Nr.	EXACT TEMPERATURE °C	OPTICAL DENSITY	ENERGY STRIKING THE PELLICULE (ergs/cm^2)
18	1	18.06	0.322	22.2
	2	18.19	0.331	
	3	18.22	0.334	
20	1	19.12	0.387	26.4
	2	19.86	0.449	
	3	20.10	0.471	
24	1	24.12	0.464	31.8
	2	24.15	0.466	
	3	24.32	0.480	
26	1	25.92	0.513	34.8
	2	26.08	0.526	
	3	26.12	0.529	
28	1	28.28	0.589	40.2
	2	28.30	0.590	
	3	28.32	0.592	
30	1	30.06	0.674	46.2
	2	30.19	0.686	
	3	30.21	0.688	
32	1	32.02	0.862	58.8
	2	32.09	0.870	
	3	32.14	0.875	
34	1	33.92	0.880	60
	2	34.01	0.889	
	3	34.14	0.875	
36	1	36.20	0.892	60.6
	2	36.24	0.896	
	3	36.25	0.897	
37	1	36.82	0.908	61.8
	2	37.00	0.926	
	3	37.09	0.935	

TABLE I



OPTICAL DENSITY
0.9
0.8
0.7
0.6
0.5
0.4
0.3
15
20
25
30
35
40
TEMPERATURE (°C)

FIGURE G

3.7 CONTINUED

Clearly the relationship between temperature and optical density is not linear. Nevertheless, only two significant figures are necessary to determine the that the temperature is within one degree once the functional relationship between temperature and optical density is known.

Since relative changes in optical density are easily measured to four or five significant figures, it is evident that measurement to 0.1°C and beyond is realistic and has been demonstrated. Moreover, the photograph (see Appendix) of actual thermal images of human hands using this new and unique method demonstrates the feasibility of this.

3.8 ESTABLISH OPTICAL CONDITIONS TO VIEW A THERMAL IMAGE

It was necessary to use a 30° angle to reflect off the pellicle. The attenuator proved to be absolutely necessary as there appears to be a delicate balance between the thermal flux and the laser flux. The procedure used is described below.

First, the second polarizer is used to observe the two maxima and minima, M and m, with the largest ratio M/m obtainable by manipulation of the first quarter wave plate. Next, the second quarter wave plate is removed and only one maximum is observed. This maximum is optimized by rotating the first quarter wave plate. Next, replace the second quarter wave plate and notice that the two maxima reappear when the second polarizer is rotated.

The ratio of these maxima can be increased or decreased by rotating the second quarter wave plate. Stop the second wave plate when the maximum difference is achieved (M/m), then return to half the smaller maximum. In this setting, the entire system will provide the maximum change in transmission for small variations in ellipticity. It is the small changes in ellipticity which are caused by local changes in refractive index at the photodichroic film. The laser beam attenuator is now used to obtain the image of best contrast.

3.9 SUCCESSFUL DEMONSTRATION OF AN UN-COOLED THERMAL IMAGER

Figure A shows the optical arrangement which was used to successfully demonstrate both the thermal imaging aspects and also the differential temperature resolution requirements of Phase I. The box, which contains a subject's hand, is for all practical purposes open to the room. While the walls were cooled to -6°C, this configuration represents an un-cooled thermal imager because the sensor is at room temperature. Conventional infrared imagers rely on sensors which are cooled to about -200°C.

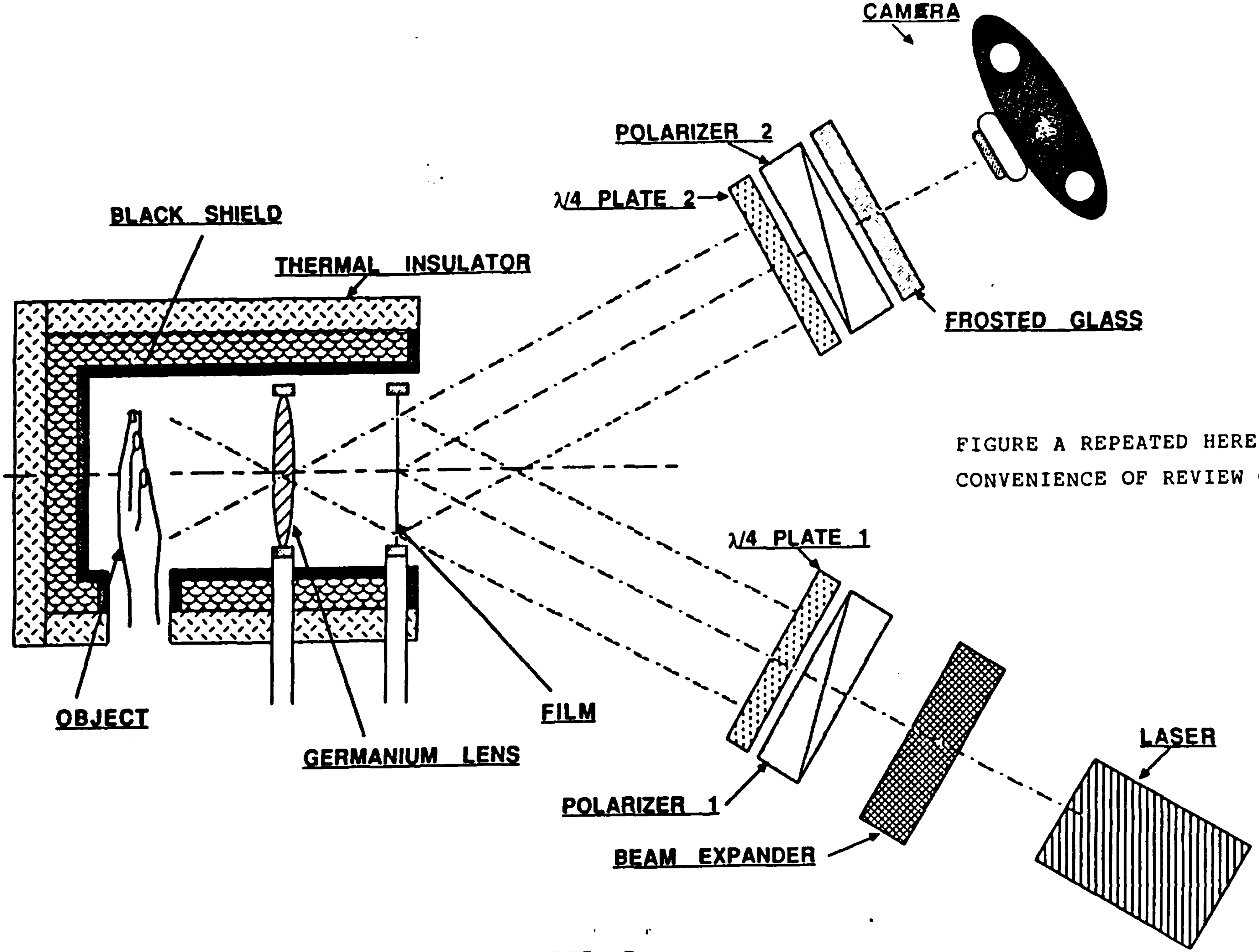


FIGURE A REPEATED HERE FOR CONVENIENCE OF REVIEW GROUP

FIGURE A

3.9 CONTINUED

By lowering the wall temperatures, the thermal background is reduced making it easier to view the image. In a practical camera design (proposed in Phase II), the walls need not be cooled although the interior of the camera will be mechanically evacuated and sealed.

Shown in Figure A is a HeNe laser which has its beam expanded and collimated before entering polarizer and quarter waveplate 1. The quarter wave plate is used to change the linearly polarized beam into an elliptically polarized beam. Next, the beam enters a simple variable neutral density attenuation filter. The attenuator is not shown. After leaving the attenuator, the laser beam strikes the pellicle at an angle of approximately 30°. From the other side of the pellicle an image of the hand is projected (via a germanium lens) onto the same pellicle.

The coating on the pellicle performs a remarkable action sensitive to the two kinds of light. The action would ordinarily be considered weak, but a very powerful technique, ellipsometry, is used for detection. Thus, a mixture of uniform intensity laser light mixes optically with thermal radiation of varying strength in a way which causes a non-linear optical effect in the photodichroic material.

The results of this effect are temporary and localized changes in the index of refraction of the photodichroic film. Where the thermal flux at the image plane is relatively low, the index is raised relatively little. Where the thermal flux is relatively high, the local index is raised relatively higher. Thus "hot" parts of the thermal image produce larger changes in refractive index than do the "colder" parts. In this way a pattern of refractive index changes occurs on the coated pellicle which is in one-to-one correspondence with the thermal image.

The uniformly elliptically polarized and laser beam reflects off the coated pellicle, but is then no longer uniformly elliptically polarized. This is because of the variations in refractive index at the film. The collimated beam is "image coded" through variations in degree of elliptical polarization.

The collimated beam passes through another quarter wave plate and polarizer combination which together comrpise what is known as an analyzer. The analyzer extinguishes light to varying amounts depending on the degree to which entering light is elliptically polarized. Thus, the collimated beam now consists of regions of varying intensity which correspond directly to the thermal image at the pellicle. The beam is visualized by a frosted glass plate.

Photographs of this image of dark and light patterns provide a permanent record of the thermal image. It is these images which are shown in plates and were used to measure the differential temperature resolution (delta T).

United States Patent [19]

Robillard

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[54] **INFRARED IMAGING SYSTEM AND METHOD**

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[21] Appl. No.: **815,810**

[22] Filed: **Jan. 2, 1986**

[30] **Foreign Application Priority Data**

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[51] Int. Cl.⁴ **G02F 1/13**

[52] U.S. Cl. **250/331**; 250/330; 350/352

[58] **Field of Search** 250/331, 330; 350/351, 350/352

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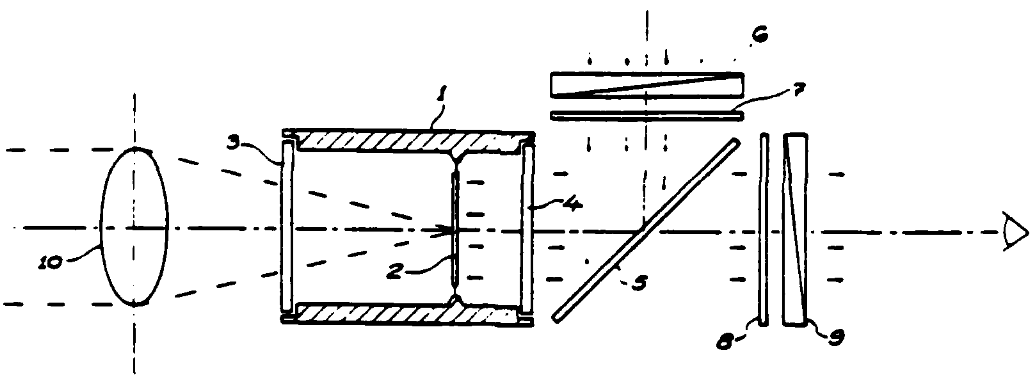
Primary Examiner—Carolyn E. Fields

Attorney, Agent, or Firm—Birch, Stewart, Kolasch & Birch

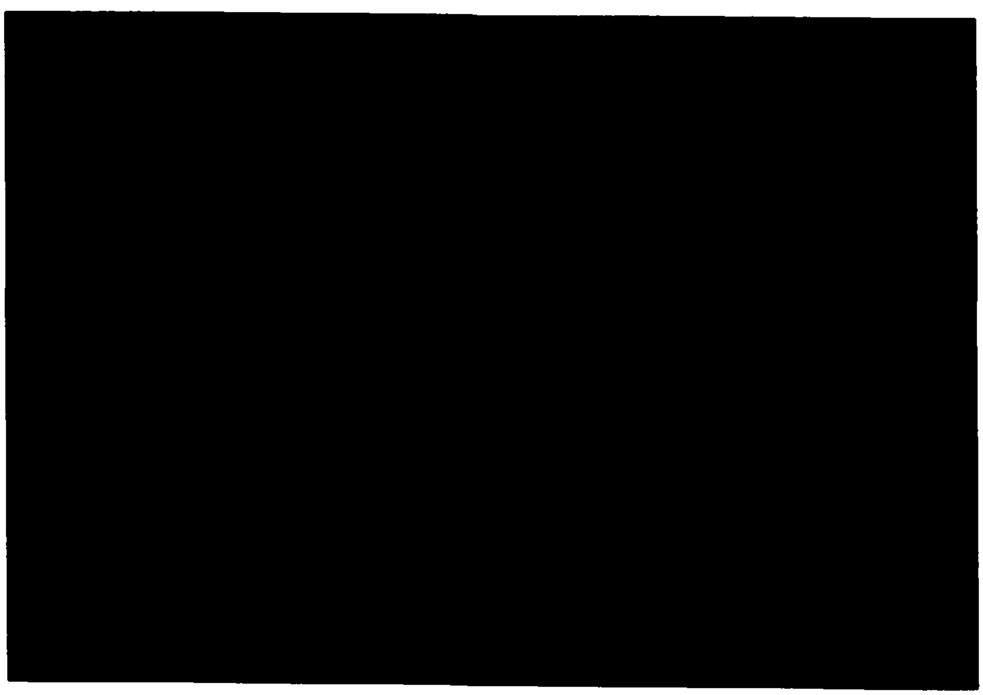
[57] **ABSTRACT**

An infrared imaging system includes a film of dichroic liquid crystal coated on a membrane, first means for forming an infrared image on the membrane, second means for illuminating the membrane with visible light, and third means for deteching variations in elliptical polarization of the light after reflection from or transmission through the membrane to provide a visible image.

17 Claims, 6 Drawing Sheets



IR IMAGE BELOW RECORDED OVER A 19°C RANGE WITH AN MRT OF 0.1°C



INFRARED IMAGING SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an infrared imaging system and method.

2. Description of Background Art

Existing infrared imaging systems can be classified into two main categories:

(a) Systems with mechanical scanning which sequentially project each point of the IR image onto a single detector. This type is the most common. It generally operates in the 10 microns range, the detector being cooled with liquid air or liquid nitrogen.

(b) Imaging tubes with a detector array where the elements of the array are scanned with an electron beam. This type of imaging device generally operates in the near infrared and requires an infrared source to illuminate the object.

Materials such as Doped Germanium or Indium Antimonide are used for detection in the former case, and Germanium or a pyroelectric material in the latter.

Systems of type (a) are complicated, bulky, expensive and require professional maintenance. Systems of type (b) are more compact and robust. They have no moving parts which simplifies the maintenance. Unfortunately their performance is limited to the near infrared.

SUMMARY AND OBJECTS OF THE INVENTION

It is therefore an object of the present invention to provide an infrared imaging system and method which does not use mechanical or electronic scanning, which operates at room temperature, and which may therefore be constructed with a considerable reduction in size and price compared with conventional systems.

Accordingly, the present invention provides an infrared imaging system comprising a film of dichroic liquid crystal coated on a membrane, first means for forming an infrared image on the membrane, second means for illuminating the membrane with visible light, and third means for analysing the polarization of the light after reflection from or transmission through the membrane to provide a visible image.

The invention also provides an infrared imaging method comprising providing a film of dichroic liquid crystal coated on a membrane, forming an infrared image on the membrane, illuminating the membrane with visible light, and analysing the polarization of the light after reflection from or transmission through the membrane to provide a visible image.

The invention makes use of the dichroism of certain liquid crystals coated on a membrane, in particular cholesteric liquid crystals. When the membrane is exposed imagewise to infrared radiation local variations of index of refraction in the liquid crystal film are produced according to the image projected. The transmission or reflection of light through the membranes produces an elliptically polarized light and the variable index pattern in the liquid crystal film causes variations of ellipticity which can be converted into variations in visible light intensity through the detecting means (detector).

The visible light which illuminates the membrane may be plane or elliptically polarized, in which case the detector will detect changes in the elliptical polarization resulting from the action of the liquid crystal. On the other hand, the illuminating light may be unpolarized, in which case the detector will detect the degree of elliptical polarization produced by the liquid crystal. In both cases the analyzer, typically a quarter wave plate and polarizer, will produce a visible image with variations in intensity corresponding to the variations in refractive index of the liquid crystal.

Where the visible light is transmitted through the membrane to the detector the membrane should be transparent to such light and it is immaterial whether the light is directed at the membrane from the side carrying the liquid crystal or from the opposite side. However, where the visible light is reflected from the membrane the latter should have a reflective coating on the side opposite the liquid crystal, with the light being directed at the membrane from the same side as the liquid crystal.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, wherein:

FIG. 1 shows the correspondence between an area ds in the aperture of an objective and an area ds' on a liquid crystal film, the perpendicular to the element ds making an angle θ with the direction ds-ds' and the perpendicular to the element ds' making an angle θ with the same direction,

FIG. 2 is a cross-section through a first embodiment of the invention operating by the reflection of polarized incident visible light,

FIG. 3 is a cross-section through a second embodiment of the invention also operating by the reflection of polarized incident visible light,

FIG. 4 is a cross-section through a third embodiment of the invention operating by the transmission of unpolarized visible light,

FIG. 5 is a perspective sectioned view of a fourth embodiment of the invention also operating by the transmission of unpolarized visible light,

FIG. 6 is a detailed cross-sectional view of the membrane and liquid crystal layer used in the embodiments of FIGS. 2 and 3, and

FIG. 7 is a detailed cross-sectional view of the membrane and liquid crystal layer used in the embodiments of FIGS. 3 and 4.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is well known that the optical properties of liquid crystals can be affected by very small amounts of energy, both nematic and cholesteric liquid crystals undergoing changes in refractive index with input energy of the order of 10^{-14} W sec/cm. Present efforts have been directed to the use of electrical energy for optical displays and thermal energy in temperature sensors and thermal mapping. However, it would be desirable to use the extreme sensitivity of liquid crystals for the detection and measurement of all kinds of radiant energies, particularly infrared energy where in the form of a thin film they would be appropriate for imaging systems. The sensitivity already achieved for thermal measurement would suggest that a ten fold improvement in detectivity over present infrared detection and imaging systems would be achieved. It would also have the advantage of simplicity and of being operable at room temperature whereas the most sensitive infrared cam-

eras have to operate at liquid nitrogen temperature and use complicated mechanical scanning systems. The best way to benefit from the remarkable sensitivity of liquid crystals for the purpose of infrared imaging would be to convert directly the absorption of infrared energy by the material into a change of refractive index that will directly modulate the transmission or reflection of light in a display configuration. In other words a thin liquid crystal film should play the dual role of infrared detection target and display screen. To optimize this function a small change in refractive index should correspond to a relatively large change in transmission or reflection of the medium. This stringent condition is fortunately encountered in certain types of liquid crystals which are dichroics. Dichroism is a phenomenon by which a light wave transmitted by the material is decomposed in two circular waves of opposite directions (left and right) with amplitudes:

$$A_r=(A/2)\ \exp.(-2\pi\nu\mu_1)d$$

and

$$A_l=(A/2)\ \exp.(-2\pi\nu\mu_2)d$$

where

A_r is the amplitude of the right wave

A_l is the amplitude of the left wave

ν is the frequency of the light

μ_1 and μ_2 are the optical absorption of the medium

d is the thickness of the film.

Because of the two different values of μ_1 and μ_2 the transmitted wave is elliptical.

In liquid crystals, particularly in certain cholesterics, the dichroism is very important and the ellipticity of the transmitted light is large. The ellipticity is an optical characteristic which depends very strongly on the index of refraction and the thickness of the film. Then, small changes in this parameter will translate into large changes in ellipticity. This dependency can be expressed by the amplitude of the two components E_p and E_s of the electrical vector E of the transmitted light wave:

$$E_p=A_p\ \exp\ j(\omega t+\delta_p)$$

$$E_s=A_s\ \exp.\ j(\omega t+\delta_s)$$

E_p: component parallel to the plane of incidence of the wave

E_s: component perpendicular to the plane of incidence.

Both the phases δ and the amplitudes A of the two components will be affected. These changes are best characterised by two parameters Δ and Ψ such as:

$$tg\Psi\ \exp.\ j\Delta=f(n_o,\ \alpha_o,\ n,\ d)$$

where

n_o is the index of refraction

α_o is the angle of incidence

n is the index of refraction of the liquid crystal

d is the thickness of the film.

The measurement of the ellipticity of the light transmitted by the liquid crystal film may be performed by an analytical set consisting of a quarter wave plate and a polarizer. The quarter wave plate converts the elliptically polarized light into two plane polarized lights which can be extinguished by the polarizer. If the polarizer is set in such a way that complete extinction is occurring when no IR is falling upon the liquid crystal then, upon receiving IR illumination, the refractive index of the liquid crystal will be changed and provide a shift of the extinction angle or, if the polarizer is fixed, an increase in transmission. If an infrared image is projected onto the liquid crystal film the change of refractive index will vary over the surface of the film thus giving rise to a variable transparency and the formation of an image in the visible spectrum.

Referring now to FIG. 1, to evaluate the sensitivity to infrared radiation of a liquid crystal imaging system, consider a liquid crystal film isolated in space and some optic projecting an infrared image on this film. To any point of the IR image will correspond a disc of surface dS corresponding to the diffraction disc of the optic. The corresponding elementary volume of liquid crystal concerned will be $dV=e\ dS$, e being the thickness of the film. The radius r of the diffraction disc is given by the expression:

$$r=\frac{1.22\ \lambda F}{H}$$

which for an aperture of F: 2 and a wavelength, λ or 10μ gives:

$$r=24\ \text{microns}$$

The diffraction disc having a surface dS of approximately 50 microns, the volume dV absorbing the IR energy emitted by the image point will be edS for a thickness e of 20 millimicrons or:

$$dV=\pi r^2 e=\pi(24)^2\ 10^{-8}\times 20\ 10^{-7}=3.6\ 10^{-11}\ \text{cm}^3$$

The heat capacity of the liquid crystal is generally of the order of 1.5 J/cm³. This indicates that to increase the temperature of dV of 1° C. the energy necessary is: $5.4\ 10^{-11}$J. This quantity corresponds to a sensitivity of $5.4\ 10^{-10}$ Watts if the change in temperature is registered in 0.1 sec. (value required for a camera with 10 images per second).

The energy emitted by the infrared scene and entering the aperture of the infrared imaging system can be evaluated considering an element dS of the source radiating infrared energy over an element dS' of the liquid crystal film. The relation between the luminance L on the surface dS and the luminous flux ϕ emitted by the surface dS is:

$$d^2\phi=\frac{L\ ds\ ds'\ \cos\theta\ \cos\theta'}{d^2}$$

where $\theta=\theta'$, θ and θ' being the angle between the perpendiculars to the surface ds and ds' respectively and the direction of propagation (See FIG. 1) and d the distance between ds and ds'.

The luminance is given by the law of Black-Body radiation:

$$dL_\lambda=\frac{C\lambda^{-2}}{\exp.(C_2/\lambda T)}d\lambda$$

which has to be integrated over the spectral range. Assuming that all the radiative energy emitted by ds is received by ds', then the total luminance L is given by Stefan's Law:

$$L=\sigma T^4$$

If the object providing the image is at room temperature (300 K.), the total luminance emitted in space by this object is:

$$L=1.8\ 10^{-8}(3\ 10^2)^4\ Wm^{-2}\ sr^{-1}$$

or:

$$L=150\ Wm^{-2}\ sr^{-1}$$

The flux ϕ received by the element ds of the LC film is then:

$$\phi=L\frac{dsds'}{d^2}=\frac{\pi}{4}(2h)^2\frac{1}{d^2}L \text{ or, for:}$$

$$H=2.5,\ h=2.5\ 10^{-7} \text{ and } d=10$$

$$\phi=6\ 10^{-8}$$

which is compatible with the sensitivity of the film.

Referring now to FIG. 2, the infrared imaging system comprises a housing 1 containing therein a membrane 2 supporting a dichroic liquid crystal film, the housing being closed by an infrared window 3 at one end and an optical window 4 at the other. The elements 2, 3 and 4 are all parallel and transverse the axis of the housing 1. The housing is evacuated to a low pressure, typically 10^{-6}–10^{-7} mm of Hg, to avoid internal thermal currents, and the interior walls are preferably made reflective so that the housing is effectively a black body and does not of itself cause thermal gradients across the membrane 2.

An infrared image at infinity is focussed by an objective 10 through the infrared window 3 onto the membrane 2 supporting the liquid crystal film thereby producing local variations of the refractive index of the film. A visible light beam from a source (not shown) is polarized by a polarizer 6 and provides a polarized light after crossing a quarter wave plate 7. The light is then reflected through the optical window 4, by a semitransparent mirror 5 disposed at 45° to the axis of the housing 1, onto the membrane 2 supporting the liquid crystal film. The latter being dichroic, causes the light reflected back by the membrane to be elliptically polarized if the orientation of 6 with respect to 7 is such that the light incident on the film is plane polarized or with a variation of ellipticity if the orientation of 6 with respect to 7 is such that the incident light is elliptical. In both cases the surface variations of the refractive index in the liquid crystal film due to the infrared absorption provides variations of ellipticity of the light reflected by the membrane, this variation being distributed over the surface of the film in direct relationship with the intensity of the infrared image received by the film. The light reflected by the membrane 2 is viewed through optical window 4 and the semitransparent mirror 5 by an detector consisting of a quarter wave plate 8 followed by a polarizer 9.

The membrane 2 and the liquid crystal film of FIG. 2 are shown in greater detail in FIG. 6. The membrane 2 consists of a thin flat sheet of transparent plastics material stretched over a metal ring 13 which is secured to the interior sidewalls of the housing 1. The liquid crystal film 11 is applied to that surface of the membrane which faces the optical window 4, the opposite surface of the membrane being coated with carbon black 12 for reflection of the visible light from the membrane. Examples of the materials which may be used for the membrane 2 and liquid crystal will be given later, together with examples of materials which may be used for the other components of the system.

In FIG. 3 the housing 2 has two optical windows 4 and 4' for infrared imaging by reflection of light at a 60° angle from the plane of the liquid crystal film. Visible incident light is reflected from the membrane 2 after crossing a polarizer 6, a quarter wave plate 7 and the optical window 4. The reflected light is viewed through the optical window 4, a quarter wave plate 8 and a polarizer 9. An infrared image is projected onto the membrane 2 carrying the liquid crystal film through an infrared window 3. The local modulation of the index of refraction in the liquidcrystal film due to the infrared absorption provides a variation of ellipticity of the elliptical light reflected on the membrane 2. This variation of ellipticity is converted to a variation in visible light intensity through the quarter wave plate 8 and polarizer 9 properly oriented. The membrane 2 is constructed as for the embodiment of FIG. 2, the liquid crystal layer 11 being provided on the surface facing the optical windows 4 and 4' and the carbon black 12 on the surface facing the infrared window 3.

FIG. 4 represents an infrared imaging system with a catoptric objective comprising a segmented parabolic mirror 16 focussing an infrared image of an object at infinite distance onto a membrane 2 supporting a liquid crystal film by reflection at a plane surface 17 and through a combined infrared/optical window 14. An annular source of unpolarized light 15 external to the housing 1 illuminates the liquid crystal film also by reflection from 17 through the window 14. The infrared image on the membrane 2 is viewed through an optical window 4, a quarter wave plate 8 and a polarizer 9.

In this case it will be observed that the incident light from 15 is not reflected by the membrane 2 but is transmitted through it to the optical window 4. Accordingly, the carbon black layer 12 shown in FIG. 6 is omitted and the membrane 2 and liquid crystal film 11 are as shown in FIG. 7. Preferably, the liquid crystal 11 is coated on the surface of the membrane 2 which faces the incident infrared radiation, i.e. the window 14.

FIG. 5 represents an infrared imaging system with an objective lens 19 for infrared radiation projecting the image of an infrared object at infinite distance onto a membrane 2 supporting a liquid crystal film and mounted in an evacuated housing 1. An annular light source 18 internally of the housing illuminates the membrane 2 by reflection from the inner surface of the infrared objective 19. The visible light transmitted through the membrane 2 is viewed through an optical window 20 in the form of a further lens followed by a quarter wave plate and a polarizer (not shown). In this case it will be noted that the infrared and optical windows which seal the opposite ends of the housing 1 are both in the form of lenses, i.e. the lenses 19 and 20.

As in the case of FIG. 5, the light from the source 18 is transmitted through the membrane 2 and not reflected by it, and therefore the membrane and liquid crystal film have the structure shown in FIG. 7. As before, it is preferred that the film 11 is coated on the surface of the membrane 2 which faces the incident infrared radiation, i.e. the objective 19.

The material used for the windows providing infrared transmission at 10 microns such as window 3 of

FIGS. 2 and 3 is preferably germanium with a thickness of from 1 to 5 mm. The material used for the window 14 of FIG. 4 providing transmission both in the infrared and visible is preferably sodium chloride or calcium fluoride. The material used for optical windows providing transmission in the visible spectrum such as window 4 of FIGS. 2 to 4 is preferably ordinary optical glass. Finally, the material used for the fabrication of objective lenses for infrared imaging such as lenses 10 and 19 in FIGS. 2 and 5 is preferably germanium.

The material used for the fabrication of the quarter wave plates is generally mica but any transparent material with proper thickness and refractive index can alternatively be used.

The polarizers used in the infrared system will be preferably of the "Polaroid" type because of the large diameter needed.

More sophisticated polarizers such as Glan Thompson prisms can alternatively be used but the price of such component will generally restrict the diameter available and the field of view.

The membrane holding the liquid crystal film can be made of various polymers such as Mylar, Farmvar, colloidion, nylon, etc. with a thickness varying from between one and fifty microns. For faster response, membranes made of materials such as the ones described in U.S. Pat. No. 2,617,513 will be preferred. Materials will then be beryllium oxide or silica with a thickness varying from 0.1 to 10 microns.

Liquid crystals used in the invention are preferably cholesteric materials chosen among the cholesteryl esters including cholesteryl acetate, carbonate, chloride, *nanoate, nonanoate, decanoate, dodecanoate, oleate*, propionate, laurate, etc. used individually or as a mixture of crystals. These have a high surface tension and may be coated on the membrane in conventional manner by applying a drop of the liquid crystal to the membrane and rolling with a glass rod. The preferred thickness of the liquid crystal film is 5 to 50 millimicrons with 20 millimicrons being preferred.

For thermal compatibility the membrane should have a specific heat C_p and thermal conductivity K close to that of the liquid crystal material used. For example, for Mylar one has:

$$C_p = 0.315\ \mathrm{Cal/g/^\circ C.}$$

$$K = 3.63\ 10^{-4}\ \mathrm{Cal/sec./cm/^\circ C.}$$

The corresponding parameters for cholesteryl propionate liquid crystal are:

$$C_p = 0.46\ \mathrm{Cal/g/^\circ C.}$$

$$K = 10^{-4}\ \mathrm{Cal/sec./cm/^\circ C.}$$

I claim:

1. An infrared imaging system comprising a film of dichroic liquid crystal coated on a membrane, first means for forming an infrared image on the membrane, second means for illuminating the membrane with visible light, and third means for detecting variations in elliptical polarization of the light after reflection from or transmission through the membrane to provide a visible image.

2. A system according to claim 1, wherein the membrane is contained within an evacuated housing, the housing including an optical window and an infrared window.

3. A system according to claim 2, wherein the first means comprises an infrared imaging system external to the housing which directs infrared radiation through the infrared window onto the membrane.

4. A system according to claim 2, wherein the first means comprises the infrared window which is formed as a lens.

5. A system according to claim 2, wherein the second means comprises a visible light source external to the housing which illuminates the membrane through the optical window.

6. A system according to claim 5, wherein the second means includes means for polarizing the light prior to illuminating the membrane.

7. A system according to claim 5, wherein the third means detects the light after reflection from the membrane and transmission through the optical window.

8. A system according to claim 5, wherein the housing includes a further optical window, and wherein the third means detects the light after reflection from the membrane and transmission through the further optical window.

9. A system according to claim 2, wherein the second means comprises a visible light source inside the housing.

10. A system according to claim 9, wherein the visible light source is arranged on the opposite side of the membrane to the optical window and the third means detects the light after transmission through the membrane and through the optical window.

11. A system according to claim 10, wherein the visible light source illuminates the membrane after internal reflection at the infrared window.

12. A system according to claim 4, wherein the optical window is also formed as a lens forming part of the third means.

13. A system according to claim 6, wherein the third means detects the light after reflection from the membrane and transmission through the optical window.

14. A system according to claim 6, wherein the housing includes a further optical window, and wherein the third means detects the light after reflection from the membrane and transmission through the further optical window.

15. A system according to claim 4, wherein the second means comprises a visible light source inside the housing.

16. A method of infrared imaging comprising providing a film of dichroic liquid crystal coated on a membrane, forming an infrared image on the membrane, illuminating the membrane with visible light, and detecting variations in elliptical polarization of the light after reflection from or transmission through the membrane to provide a visible image.

17. An infrared imaging system comprising:

a film of dichroic liquid crystal coated on a membrane;

first means for forming an infrared image on the membrane;

second means for illuminating the membrane with visible light; and

third means for detecting variations in elliptical polarization of the light after reflection from or transmission through the membrane to provide a visible image.

said membrane being contained within an evacuated housing, said housing including an optical window transmissive of visible wavelengths and an infrared window, said infrared window also being transmissive of visible wavelengths,

said first and second means directing infrared and visible light, respectively, through said infrared window onto the membrane, and said third means detecting the light after transmission through said membrane and through said optical window.

* * * * *

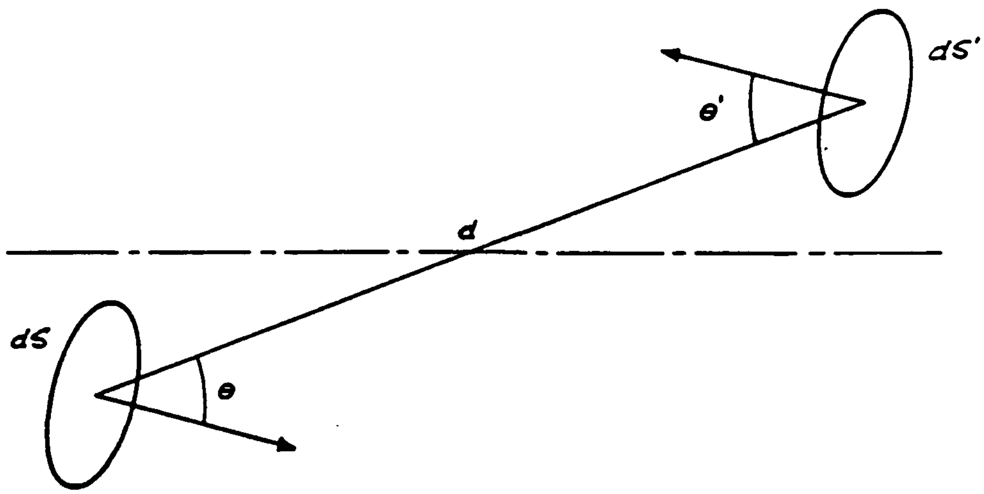


FIG. 1

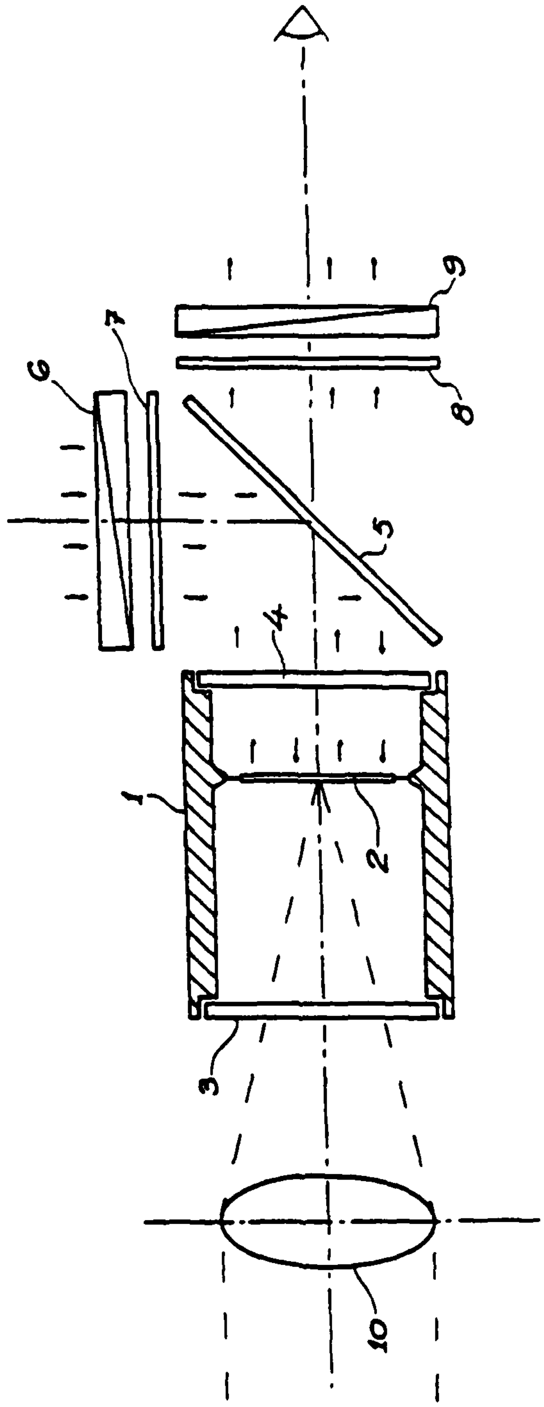


FIG. 2

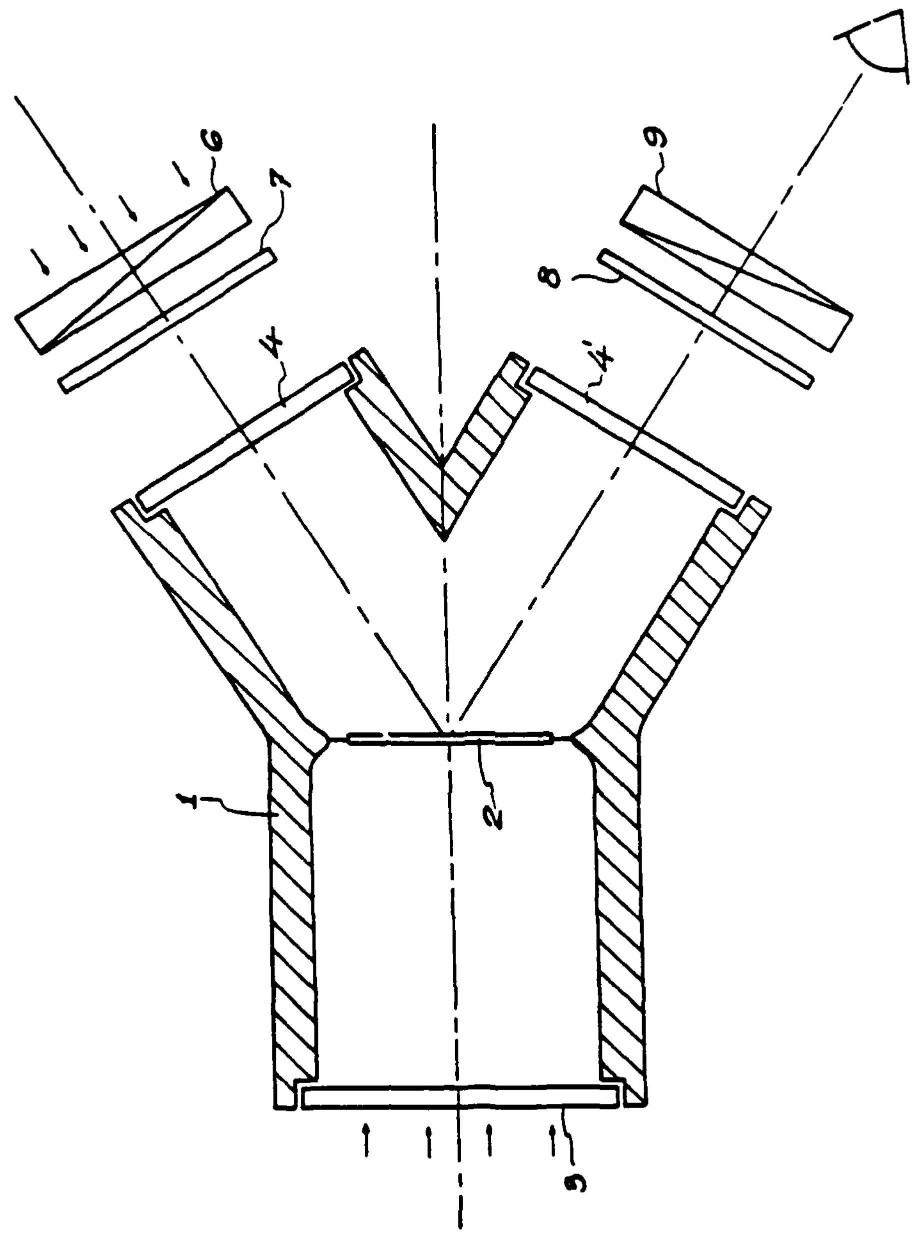


FIG. 3

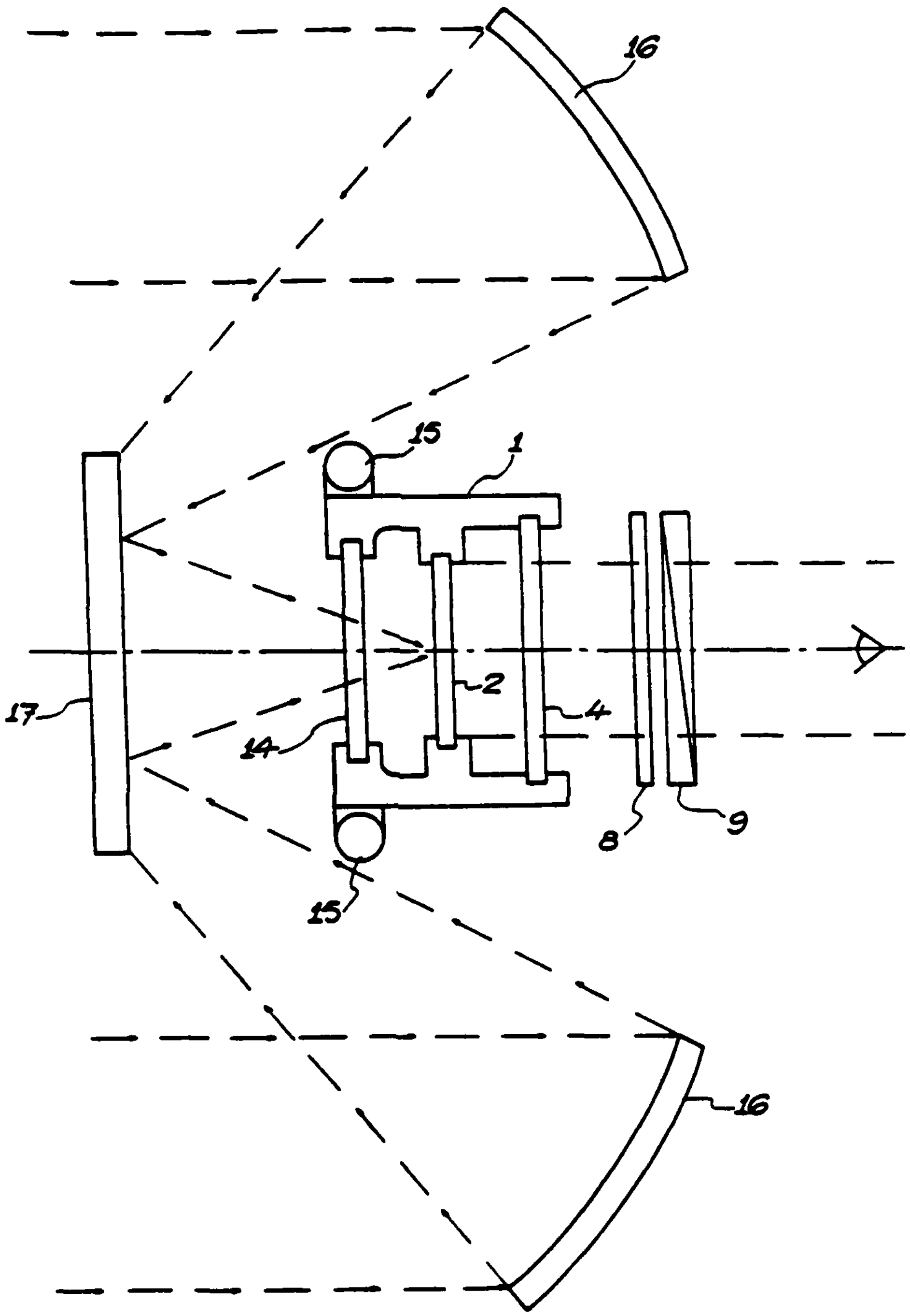


FIG. 4

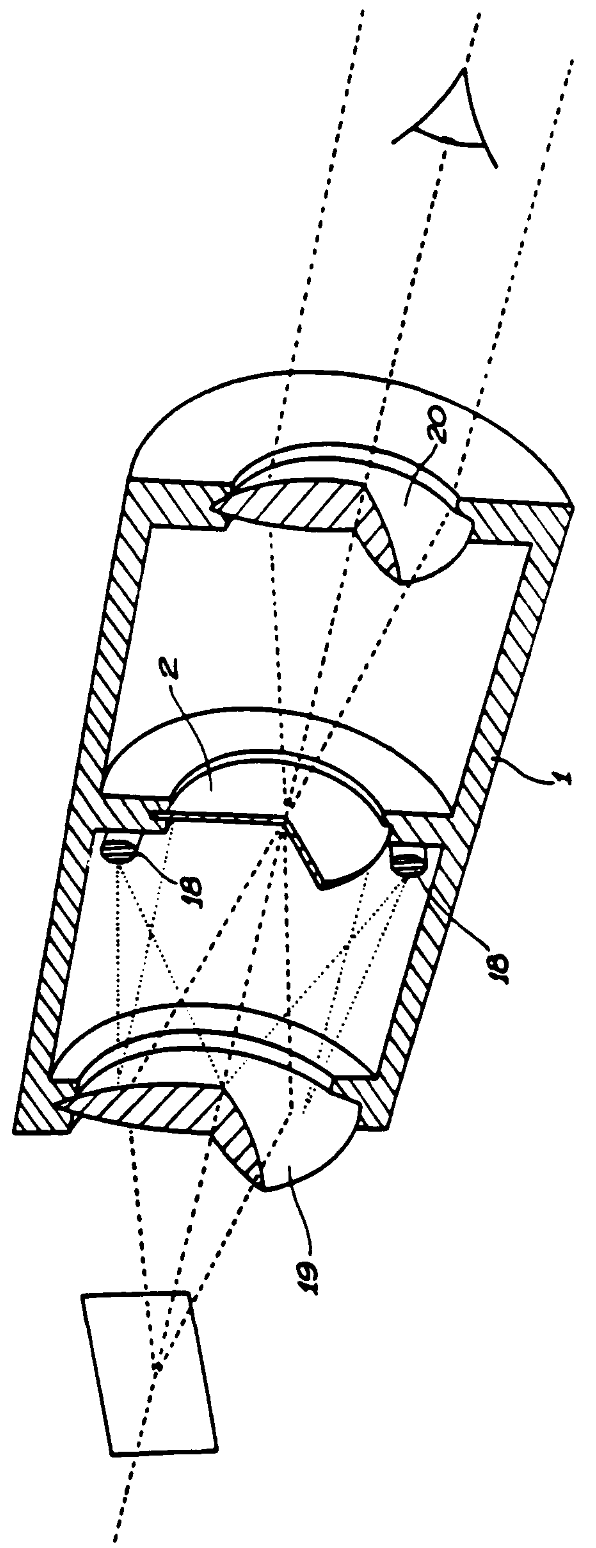


FIG. 5

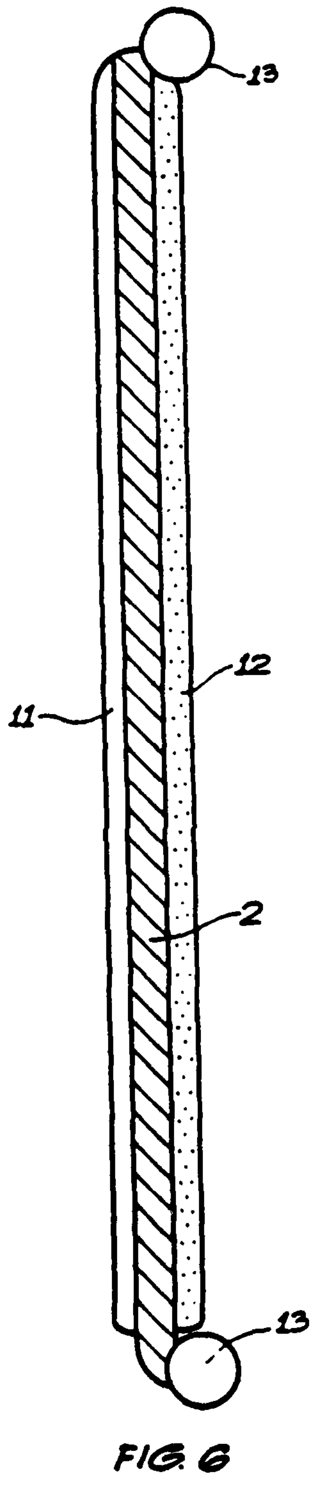


FIG. 6

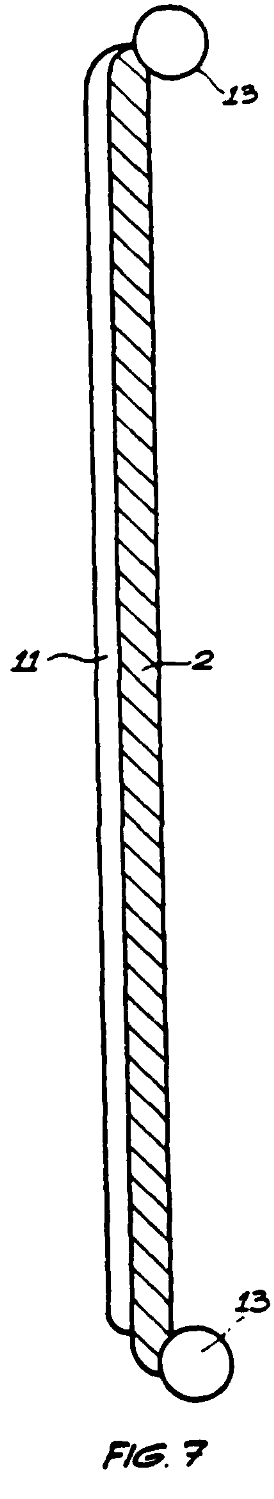


FIG. 7